Global Ionospheric Perturbations Monitored by the Worldwide GPS Network

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Abstract. For the first time, measurements from the Global Positioning System (GPS) worldwide network are employed to study the global ionospheric total electron content (TEC) changes during a magnetic storm (November 26, 1994). These measurements are obtained from more than 60 world-wide GPS stations which continuously receive dual-frequency signals. Based on the delays of these signals, we have generated high resolution global ionospheric TEC maps at 15 minute intervals. Using a differential method comparing storm time maps with quiet time maps, we find that the ionosphere during this storm has increased significantly (the percent change relative to quiet times is greater than 150%). During this particular storm, there is almost no negative phase. A possible traveling ionospheric disturbance (TID) event is identified that propagates from high latitudes (subauroral region) to low latitudes covering a large latitude range (- 300). This TID is coincident with increases in the TEC and the, peak density of the *F* region (N_mF). Two regions of strong TEC enhancement occurred in the pre-dawn and noon sectors in the northern hemispheric subauroral latitudes, immediately after the storm main phase onset. This pre-dawn peak then migrated into a subauroral (~60°N) enhancement region during nighttime, while the dayside peak. which is caused by the TID shifted equatorward down to 30°N with a speed of -460 rids. "l'he TEC increase in the subauroral region is also noted in the southern hemisphere, but the positive effect at other latitudes is weak. The global TEC increases lasted for about 2 days, and then a weak decrease followed, These preliminary results indicate that the differential mapping method, which is based on GPS network measurements, appears to be a useful tool for studying the global pattern and evolution process of the entire ionospheric perturbation.

Introduction

Dual Frequency Global Positioning System (GPS) measurements have been used by several investigators to study the ionosphere [Lanyi and Roth, 1988; Wilson et al., 1995; Coker et al., 1995; Kelley et al., 1996]. Data from a worldwide network of GPS sites makes it possible, for the first time, to map accurately global ionospheric variability. Currently more than 60 global GPS stations receive dual-frequency signals from GPS satellites continuously, Based on the dispersion of the received signals, high resolution interpolated TEC maps or Global Ionospheric Maps (GIM) can be produced every 15 min (or more frequently) [Mannucci et al., 1996]. These maps can be used for studying global ionospheric disturbances during geomagnetic storms, among many other applications.

Since the first study of an ionospheric storm using radio frequency signals [e.g., Anderson, 1928], tremendous effort has been made to classify and interpret the observed ionospheric disturbance effects [e.g., Essex et al., 1981; Fuller-Rowell et al., 1990; Buonsanto et al., 1990; Prolss et al., 1991]. Today, various experimental techniques have been used to study the global structure of the ionosphere. Substantial data bases of TEC data have been collected from Faraday rotation measurements at several stations [e.g., Mendillo, 1971; Mendillo and Klobachar, 1975; Lanzerotti et al., 1975; Titheridge and Buonsanto, 1988]. The ionospheric density, temperature, ion drift velocity and neutral wind speeds are measured by incoherent scatter radar and Fabry-Perot interferometers. Based on these measurements, some empirical and semi-empirical models have been proposed, such as the Bent [1976] model, the International Reference Ionosphere (IRI-90) model, etc. Some theoretical models have also been developed to explain the large-scale temporal and spatial structures [e.g., Anderson, 1973; Schunk, 1988; Bailey et al., 1993].

However, day-to-day variability (particularly during storm times) is neither well understood nor well described yet. This is partially because of the complexity and the variability of the ionosphere, which is due to many different mechanisms, such as dynamo electric fields, polar auroral processes, plasmapause motion, solar EUV variation, and neutral wind propagation. Understanding these processes, which are coupled on global scales, requires a near real-time global monitoring system. Previous ionospheric studies have been based primarily on measurements from single or local station chains, Researchers in the past were forced to organize their findings from these stations to obtain a global picture. Single orbiting satellites carrying ionospheric sensors also cannot monitor the response of the global ionosphere to magnetic storms because of the lack of instantaneous global coverage.

Ionospheric storms have been observed to include both a positive (TEC or electron density increases) and a negative (TEC decreases) phases. The occurrence of these phases depends largely on season, location, storm intensity, and local starting time. The positive phase usually takes place in the early stages of a storm. in the polar region, Joule heating due to the electric currents and/or by particle precipitation will cause an increase in the atmospheric pressure at high latitudes. A meridinal wind is usually generated in the polar region and carried by fast-moving traveling atn~osphcric/ionospheric disturbances (TAD/TID) to lower latitudes. The enhanced equatorward winds will lift the plasma to higher altitudes in the *F*-region ionosphere. This upward drift may also be caused by dayside magnetospheric convection electric fields [Earle and Kelley, 1987; Pi et al., 1993]. In contrast, the negative storm phase often takes a longer period to develop. Neutral compositional changes are responsible for this relative decrease in TEC [e.g., Burns et al., 1991; Prolss et al., 1991]. Changes in thermospheric circulation and composition can cause O/N_2 ratio decreases in the middle ionosphere, leading to a decrease in the *F* region plasma density.

Using simultaneous global observations to monitor the ionosphere, such as is done with extensive ground-based GPS networks has many advantages in studying the global evolution of ionospheric storms. Wc can easily identify the global variations of ionospheric TEC during a magnetic storm, including its motion, expansion, and intensity. This can aid in classifying and interpreting these global changes. Wc have observed changes in TEC that clearly reflect the ionospheric disturbances. In this paper wc will report a global ionospheric perturbation event occurring during the geomagnetic storm on November 26, 1994, monitored by the GPS global network, which shows the potential value of GPS data in such studies.

Data and Method

The GIM, a data-driven interpolated map of ionospheric TEC measurements, is a relatively new ionospheric retrieval technique based on data from a global GPS network of 60+ stations [Mannucci et al., 1993; Wilson et al., 1995]. The GPS constellation consists of 24 satellites at 22000 km altitude. These satellites continuously broadcast dual-frequency (1 .57542 GHz and 1.2276 GHz) signals for navigation purposes. The GPS stations operate continuously as part of the international GPS service or IGS network [Zumberge et al., 1994]. Each station may receive signals from up to 10 GPS satellites simultaneously (typically 6-7 satellites arc tracked at any one moment). Thus, from the inter-frequency delay of the signals, the ionospheric total electron content (TEC) along the lines of sight between 400+ receiver and satellite pairs are measured simultaneously. These signals are recorded every 30 seconds and arc transferred to data centers generally within *24* hours (or faster). Both carrier phase delays and group delays are used to derive the TEC integrated along the line of sight, Using a Kalman filter-based fitting procedure, these TEC measurements arc interpolated to produce global ionospheric TEC maps [Mannucci et al., 1996]. The typical line-of-sight error is within 2 TECU in most global regions [Ho et al., 1996]. Based on these TEC maps, ionospheric variations with small scales can be studied, particularly, in local regions where a high density of GPS stations may be available [e.g., Calais and Minister, 1995]. However, in this study, wc will focus on large global scale perturbations.

In order to clearly identify the ionospheric variations during magnetic storms, wc have developed a differential mapping technique (DMT), which computes the percentage change in TEC during the storm time relative to TEC maps generated during quiet days. To obtain the quiet time data base, wc averaged 5 days (Nov. 21 - 25) of TEC measurements obtained via GIM, for days associated with very low magnetic activity (daily sum $\Sigma Kp <$ 15). At any particular time and location, the storm time TEC is compared with the quite time profile, taking into account quiet time variability. These global percent change maps arc in this case plotted every 15 minutes. The DMT will be described in more detail in a future publication.

in this study, wc also used the direct ionospheric TEC measurements made by Topex satellite as a reference to examine the accuracy of GIMs. The Topex has an onboard dual-frequency radar altimeter which precise] y measures the sea-surface height after removing an ionospheric correction. Topex's orbit is relatively fixed in local time changes only by about 10 min per day). Topex gives a measurement of ionospheric vertical TEC every second over a wide latitude range. The altimeter data have been smoothed into 12 second averages. Wc have directly compared it against the interpolated, mapped to vertical TEC measurements obtained with the GIM method,

in addition, wc have also compared our GPS measurements with ionosondc data available simultaneously in certain longitude sectors. The time variations of the interpolated TEC values from GIM are compared with the changes in the N_mF_2 (peak density of the F_2 layer) determined from ionosonde stations in various latitude regions, as shown below.

observations

The magnetic storm studied occurs on November 26, 1994. Observations from the WIND spacecraft indicate that the interplanetary magnetic field B_z component at 0600 UT had a large variation associated with a high speed solar wind stream and a magnetic compressed region. The ground magnetic field measurements show that a sudden commencement occurs at -0700 UT, while the main phase of the storm starts at 0900 UT, At 1300 UT the Dst index reaches its maximum value of 122 nT. The maximum Kp is 6^+ in the 0900-1200 UT interval, The storm slowly recovers and the Dst index reaches its quiet time value on December 2. Figure 1 shows the magnetic field (1 I component) measured around the northern auroral region, the Dst index and the Kp index during this storm.

An analysis of the differential ionospheric maps shows that no large (> 20% increase relative to the quiet time map) TEC changes arc found before the storm onset. At 0830 UT, two peaks (range from +80 to +100%) appear within 15 minutes, in the pm-dawn and morning sectors (north American and north European areas) around subauroral regions (60 °-70°N, geomagnetic latitude). The two peaks are later identified as that one (nightside) is a subauroral enhancement, while another (dayside) is a TID. Then the peaks become. stronger ancl the enhanced regions become larger. At 1 100 UT, the two peaks nearly connect and then cover all regions from post-midnight to noon at subauroral high latitudes. The daytime peak shows a clear equatorward expansion during next two hours,

Based on the differential TEC maps, we find that at 1300 UT the dayside enhancement reaches its maximum value (~+ 150%), coincident with the maximum deviation in Dst. In Figure 2 we give the percent TEC change map at 1345 UT. We have used a sun-fixed longitude and a geographic latitude to show the TEC changes. Local noon is in the center of the Figure (i.e. sun-fixed longitude 0°). The gray dots give the locations of the GPS stations. We can see (hat significant TEC changes occur in the northern hemisphere. The dayside peak has extended from 60”N to 30”N across latitudes. We also see the strong (> -t-1 00%) enhancements around the subauroral region - 60”N in the nightside. The TEC changes in the equatorial and ow latitude regions arc not significantly larger than the quiet time variations.

We further find that at 1600 UT, the dayside enhancement disappears, and only the nightside subauroral region enhancement remains. At its conjugated latitudes of the southern hemisphere, there is also a TEC increase. The phenomena of the conjugated enhanced TEC has been noted by many previous studies (e.g., Tanaka, 1979). When these are displayed in a coordinate system containing geomagnetic latitude, the increased TEC in the subauroral region has been observed to persist at nearly constant latitudes (--60°) in both hemispheres. This feature lasts until 0700 UT on November 27. It is then followed by a small decrease. During this period, some latitudinal structures in mid and low latitude regions are also seen.

We may compare this storm sequence with some past studies. For example, Schodel et al. [1974] found that the storm of December 17, 1971 has the largest positive (by factors of 2-3) phase ever recorded at many of the individual ionosonde stations. Essex et al. [1981] examined a summer storm (northern hemisphere) and also found that the TEC enhancements were large in the winter (southern) hemisphere, The depletion in TEC are generally more severe in the summer hemisphere. Prolss and Zahn [1977] showed that in summer, the thermospheric disturbances related to the negative phase of the ionospheric storms may extend to lower latitudes. We find that the storm studied here is also one with large positive percent changes in the northern (winter) hemisphere coupled with a very weak negative phase.

in order to assess the accuracy of the GIM measurements, we have compared TEC values derived from GIMs with other independent measurements from both satellite and ground stations. The ionospheric absolute TEC values from GIM and Topex during both storm (top) and quiet (bottom) times arc plotted in Figure 3. Because of the limit of Topex's orbits, this comparison can only be made above the ocean where GPS stations arc largely absent, On Nov. 25 and 26, Topex had trajectories along the Eastern Pacific Ocean from the Aleutian Islands at post-midnight, through east Hawaii to the east of Easter Island at pre-noon. From the top figure, we see that the interpolated TEC values from GIMs follow the measurements from Topex reasonably well. During the storm, two TEC peaks are visible from both measurements of GIMs and Topex at around 40°S and 30°N, that have increases of +80% and +100% relative to the quiet time profile shown in the bottom panel of the figure, respectively. These two enhanced regions over the Fast Pacific ocean may also be identified in the differential TEC map of Figure 2. The bottom figure shows a quiet day profile with a similar trajectory and local time coverage as the top figure. We have also plotted TEC predictions from the Bent model along the Topex track, As expected, the climatological model does not follow the TEC enhancement present during the storm time. During the quiet period, the two measurements and the model's predictions show similar profiles in this latitude and local time range.

A direct comparison of the global ionospheric TEC maps with ground-base ionosonde N_mF_2 measurements is shown in Figure 4. We have selected the ionosonde station chain at 15°E longitude (LT = UT+ 01) in northern Europe. Comparisons are made for three days (Nov. 25- 27) as a function of universal time. No GPS stations arc in this case co-located with the ionosonde stations (scc the map in Figure 2 for the locations of GPS). The absolute TEC values at the geomagnetic latitudes of the ionosondes arc obtained through an interpolation from the measurements of the nearby GPS stations (automatically provided via the GIM approach). It appears that the broad enhancements in TEC arc coincident with enhancements in N_mF_2, both before and after the storm. On Nov. 26 (storm day), TEC profiles measured from GIMs have a maximum at the same time as N_mF_2 at the three ionosonde stations. Note that these peaks show a clear shift from high latitudes to low latitudes within a two hour interval. However, the ionosonde data shows more variations than GIMs. This may be due to the smoothing and interpolation inherent in the GIM technique, or possibly because TEC is an integrated density that averages over many layers. Note that at the higher latitudes, at station Lycksele, there is strong ionospheric absorption during the storm.

Using these GIMs and the differential mapping technique, we can study TEC perturbations in a particular longitude sector propagating from high to low latitudes. In Figure 5, we have plotted the percent TEC changes at 0° geographic longitude (Greenwich meridian) in the northern hemisphere averaged over a 10° latitude band, This allows us to examine the latitudinal propagation of the disturbance. Wc use a vertical line to show the start time of the main phase of the geomagnetic storm in the Figure. As wc stated before, the enhancements at high latitudes of the northern hemisphere starts immediately after storm onset. The positive phase is very strong (exceeding +150% in the 50°-600 band), while there is almost no negative phase, during the entire storm period. The peaks between the 60° and 30° latitudes have a delay of about two hours, as can be seen in Figure 4. We may explain this shift as being caused by a TID that is propagating from high to low latitudes at a speed of 460 m/s. "l'his equatorward expansion speed turns out to be a typical TID speed [Prolss et al., 1991].

Summary

A number of advanced techniques have been used over the years to measure various thermospheric/ionospheric parameters (such as incoherence scattering radar) at mostly a few individual sites. The worldwide GPS network, the GIM and the DMT methods, however, allows for near instantaneous monitoring of global ionospheric TEC changes. These global observations may provide important input for space weather monitoring and early warning of large ionospheric variability, specially during severe storm periods. We have used TEC measurements from this new technique to reassess the topic of the ionospheric storms. We appear to have found many characteristic features of the ionosphere during storm times, such as subauroral enhancements, dayside mid-latitude expansions associated with 1'111s, and conjugated latitude enhancements. We summarize these important features for the storm of November 26, 1994 as follows.

1, This storm event has a strong positive phase (> + 150%) and an unusually weak negative phase (- -2070), compared to storms studied in the past.

2. We find that the daytime TEC enhancement region moves equatorward from subauroral latitudes down to 30°N in about 2 hours, This is consistent with a TID speed about 460 m/s.

3. At subauroral latitudes (- 60°) in both hemispheres, simultaneous TEC enhancements arc detected over the entire nightside and last for more than 10 hours.

TEC values derived from GIM techniques show a good agreement with independent Topex altimeter measurements. We have also compared TEC data from GIMs with ionosonde data. We find that both measurements have similar local time patterns. Compared with other techniques, however, the IGS network currently has a much larger global coverage and higher time resolution. The DMT method (based on GIM differences) has a potential usc in a global storm monitoring and warning systems, due to its global coverage, potential for instantaneous feedback of ionospheric variations and since the measured TEC changes more directly affect the radio signal's propagation. Currently, there are more than 60 GPS stations all over the world. The numbers of stations have increased by a factor of 2 between 1993 and 1995. Real-time global ionosphere measurements and maps derived from GPS network data with high temporal and spatial resolutions should be available soon.

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Figure Captions

Figure 1. Geomagnetic Indices for the magnetic storm on November 26, 1994. The top panel shows H component variations from 6 ground magnetic stations around the northern aurora] region. The middle panel is the three hour Kp index, while the lower panel gives the Dst index during this storm.

Figure **2.** A global percent ionospheric TEC change map at 1345 UT, Nov. 26, 1994. The map gives a 15 rnin average of TEC changes relative to the quiet time. In the northern hemisphere, TEC shows significant changes. Two large enhanced regions are seen at post-midnight and noon respectively.

Figure **3.** A comparison of TEC measurements from GIMs, Topex and the Bent model along a Topex trajectory. We see that during the quiet time (lower panel), three measurements have consistent profiles. However, during the storm time, TEC data deduced from GIMs fits the direct measurements from Topex, but has a large difference from Bent.

Figure 4. A comparison of three day profiles of TEC from GIMs and N_mF_2 from three northern European ionosonde stations (1 TECU = 10^{20} el./cm^2). Three ionosonde stations have the following geographic coordinates, Rome (4 1.8"N, 12.5°E), Juliu/Ruegen (54.6°N, 13.3°E) and Lycksele (64.6°N, 18.7°E).

Figure 5. A latitude dependence of percent TEC changes relative to the quiet times along the Greenwich meridian. Only northern hemispheric variations arc shown in 10° latitude bins. After the storm main phase onset, the TEC peaks progressively shift from high to lower latitudes, which suggests a TID propagation equatorward.

Geomagnetic Activity Index of Magnetic Storm on Nov 26, 1994

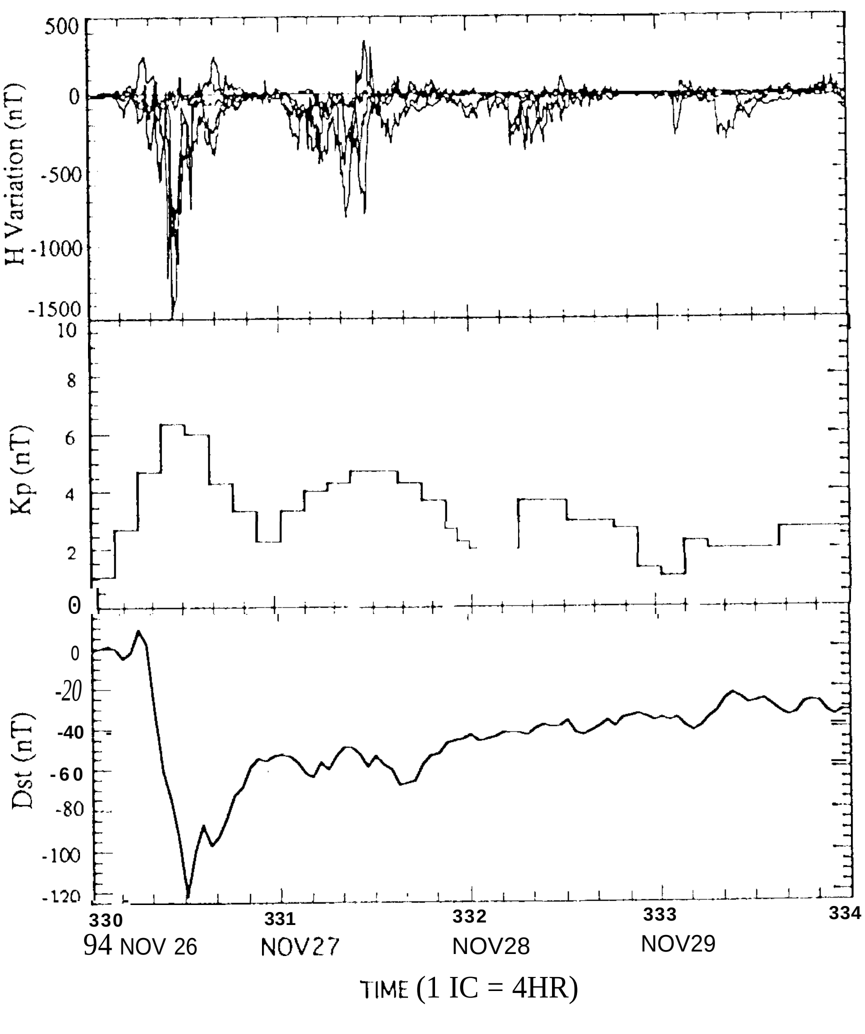
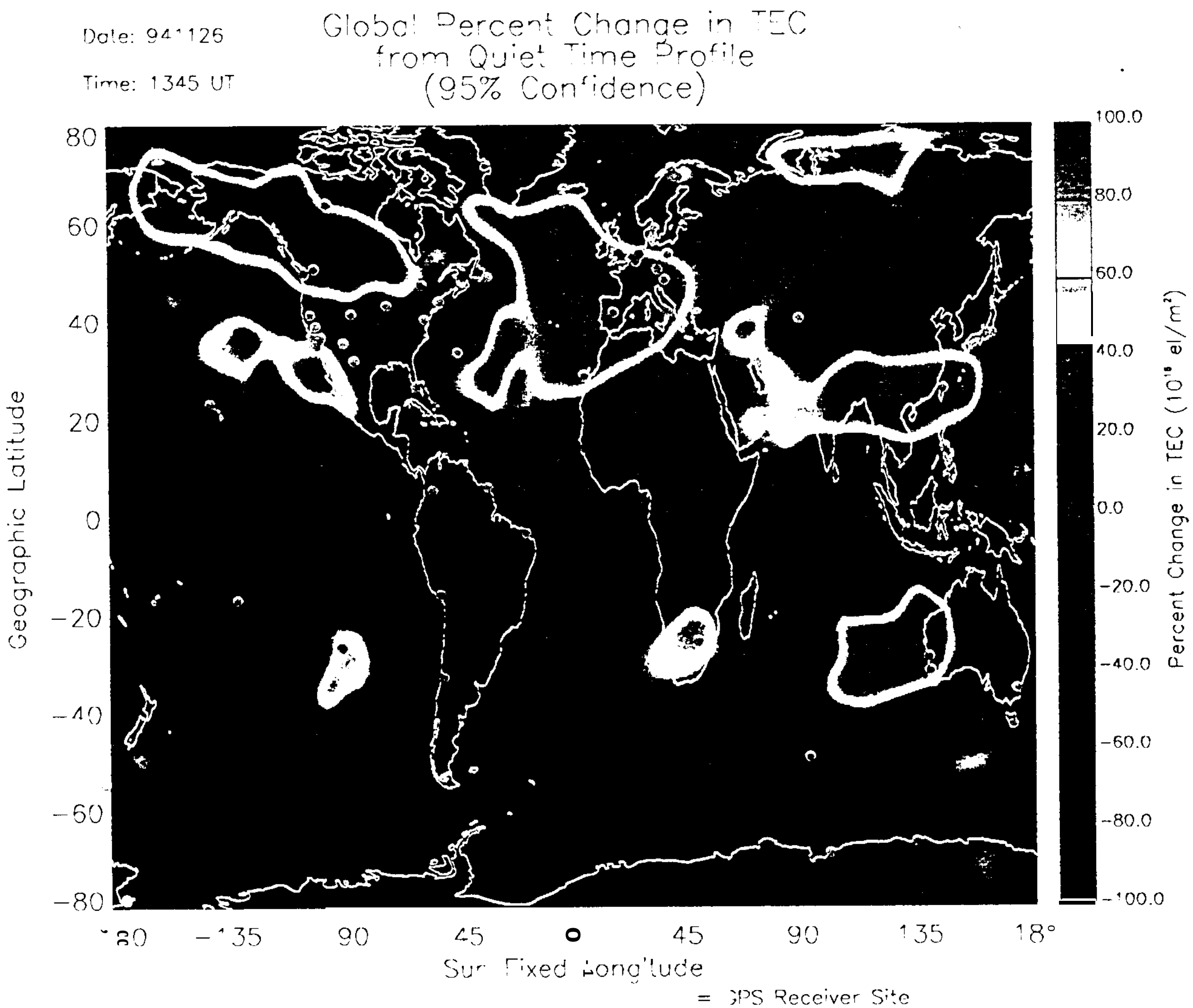


Figure 1.



Date: 941126
Time: 1345 UT
Global Percent Change in TEC
from Quiet Time Profile
(95% Confidence)
Geographic Latitude
80
60
40
20
0
−20
−40
−60
−80
135
90
45
0
45
90
135
Fixed
100.0
80.0
60.0
40.0
20.0
0.0
−20.0
−40.0
−60.0
−80.0
Percent Change in TEC
Receiver Site

Figure 2.

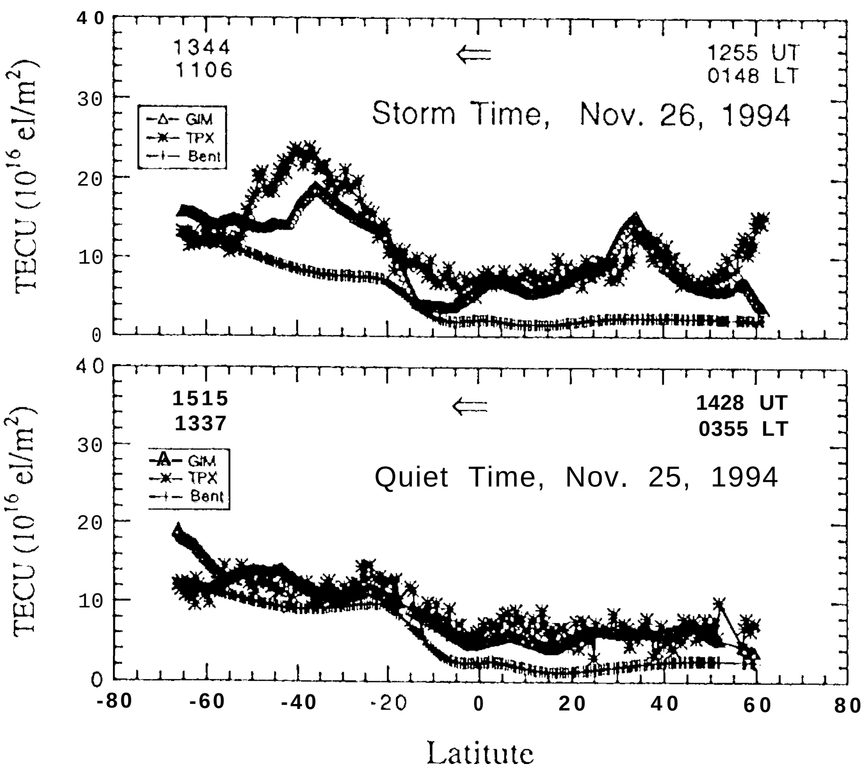

1344
1106
1255 UT
0148 LT
Storm Time, Nov. 26, 1994
GIM
TPX
Bent
TECU (10^{16} el/m^2)
1515
1337
1428 UT
0355 LT
Quiet Time, Nov. 25, 1994
Latitute

Figure 3